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External electric field effect on energy level positions in a quantum well

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Abstract. The effects of an electric field on quantum well (QW) potential profile and position of bound states there are investigated. It is shown, that the electric field applied on a symmetrical quantum well transforms it into asymmetrical one, and at strong electrical field — into triangular one, and the energy of a bound state decreases with an increase of field as long as the level of energy remains in quadrangular well region. In strong electrical fields the energy level are shifted into triangular well region, that determines the increasing of bound state energy concerning the well middle with field increasing.

The external electric field applied on quantum well structure changes their potential profile and, therefore, level positions there. The symmetric QW in presence of an electric field becomes asymmetrical, and the wide rectangular QW can be transformed in triangular one with corresponding energy spectrum. The considerable attention [1–6] was given to a problem of study of an electric field influence on an energy distribution in QW structures. It is known that the energy spectrum of QW structure could be determine by means of photo or electroluminescence measurements [1, 3]. Disadvantages of these methods are concerned, firstly, with involving to the luminescence process two types of charge carriers (electrons and holes), that considerably complicates a problem of an evaluation of electron or hole energy spectrum, secondly, for many QW structures it is rather difficult to observe the luminescence. The technique recently offered by us [7], allows to determine energy level positions by applying electric field on the quantum well structure for hole and electron wells independently.

In the present paper we study the influence of an electric field on energy level positions in QW structures.

The measurement of a level position in QW structure under external electric field was carried out with the help of a procedure [7]. The technique is based on a screening effect of an external electric field applied on structure by charge carriers localized in the well. Low-frequency capacitance–voltage (CV) measurements of QW structures are made. If a width and depth of well are known, the procedure allows to reconstruct the QW potential profile and to determine an energy level position by a given magnitude of an external electric field.

The experimental study were performed on Si/Ge structures with a Schottky barrier. Samples were grown in conventional molecular beam epitaxy (MBE) system "Katun". The Si and Ge layers were deposited on n-doped Si (100) substrate with resistivity of 7.5 Ωcm. First a 90 nm-buffer layer was deposited at temperature of 850°C. Then temperature of the substrate was reduced up to 500°C and Ge layer with thickness of $2a = 5$ nm was grown. Finally the 20 nm-thick undope Si cap was deposited. The CV measurements performed on this structure have shown that Ge layer in the given structure forms an electron quantum well with depth of $W = 65$ meV. If we assume an electron effective mass in Ge layer equal

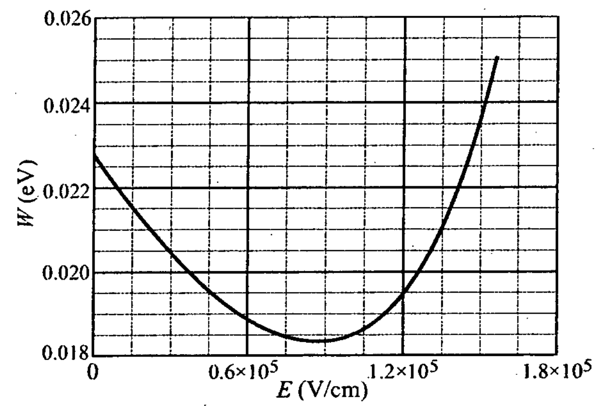

Fig. 1. Electric-field effects on level positions in quantum well (corresponds to point 2).

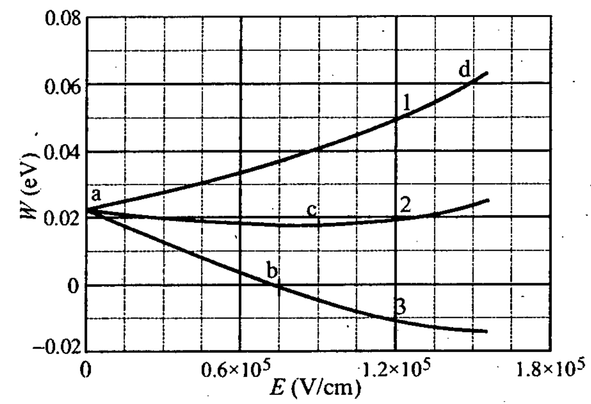

Fig. 2. Electric-field effects on level positions in quantum well (corresponds to points 1, 2, 3).

to an electron effective mass of balk material ($m^* = 0.22m_0$), we obtain in QW only one level with an energy $W_x = 23$ meV counted from the well bottom.

Figure 1 shows the external electric field effects on the energy level position in QW. The level position is counted from middle of the well bottom (point 2 in Fig. 3). In Fig. 1 we can see that in weak electric field region the energy of a bound state in QW decreases. Then at an electric field of $E = 10^5$ V/cm the level energy counted from middle of the well bottom begins to increase. The same result have been obtained in [2] although in [1, 3, 4, 6] have been found, that with increasing of an electric field the level energy decreases. In Ref. [2] the influence of the electric field on level positions in QW with various depths was studied theoretically. The Schrödinger equation in an effective mass approach for a particle with a charge e and mass m^* in the quantum well of width $2a$ and depth W was solved and it was revealed that for QW of depth $W = 70$ meV in present of strong electric fields the energy of level counted from the middle of well bottom increase. Physically such behavior of level position changes in shallow quantum well remained not clear.

The reason of such unusual behavior of level position in QW at the applied electric field increasing is due to QW structure potential profile changes. The interpretation of changes in energy level position and potential profile of OW with applied external electric field becomes easier if we plot energy level positions for following well regions (counted from

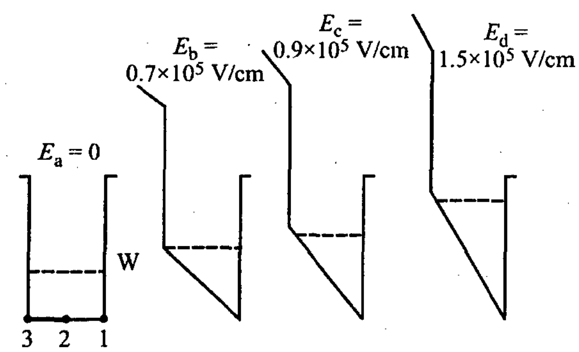

Fig. 3. Potential profile of quantum well and bound state position there as a function of applied electric field.

Schottky barrier, see Fig. 3): the point 1 is the most distant from barrier well wall; the point 2 is in the middle of well; the point 3 is the nearest to the barrier well wall. This is illustrated in Fig. 2 for cases mentioned above (curves 1, 2, 3 respectively). The curve 1 differs from the curve 2 on magnitude of a potential energy (eaE), and the curve 3 differs from a the curve 2 on magnitude ($-eaE$), where e is an electron charge, a is QW half-width, E is electric field. Thus if we know a level position in a quantum well, and we take into account, that a potential of the well bottom in points 1 and 3 differs from each other on magnitude ($2eaE$), it is possible to find the potential profile of QW and positions of a level there for a given value of an electric field.

Let us consider level positions as a function of energy for electric fields of $E_a = 0$ V/cm; $E_b = 0.75 \times 10^5$ V/cm, $E_c = 0.9 \times 10^5$ V/cm, $E_d = 1.5 \times 10^5$ V/cm. At E_b the level energy in QW is equal to zero, if the energy is counted from a point 3. The energy level for E_c is a minimum if the energy is counted from point 2. The field of E_d is a random sampling, that allow define the QW potential profile and energy level positions in the present of strong electric fields. In Fig. 3 are shown QW profiles for all four cases mentioned above.

It follows from Fig. 1 that for electric field of E_b the rate of energy decreasing with increase of field falls, thus the energy level from rectangular well region transform in triangular one, and for electric field of E_c the level is deeply buried in triangular region of QW. With an increase of electric field the triangular region of well becomes narrower the level energy arises (see Fig. 1).

Thus in the presence of external electrical field a considered symmetrical well becomes asymmetrical, and moreover triangular if the electric field is strong and the energy of a bound state decreases with the field increase (Fig. 1) as long as the energy level remains in quadrangular region of the well. In strong electrical fields the energy level is shifted into triangular region of the well, that defines the increasing of bound state energy concerning the well middle with an electrical field increasing.

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